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Application of modern methods in power plant simulatioı

Donne, M.S. Pike, A.W. Savry, R.
Technol. Centre, Alstom Power, Leicester;

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Abstract
A range of advanced simulation tools is now available which facilitates the modelling and systems. The authors' companies have been utilising the versatility of two such products industrial combined heat and power (CHP) plant. The potential benefits include improven design, control system design and in-process operation. This article describes two projec specialised power plant simulation tool ACSL/MMS has been used. In the second projec was used to analyse and undertake control design studies on power plants originally sim ACSL/MMS

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Application of modern methods in power plant simulation and control

by M. S. Donne, A. W. Pike and R. Savry

A range of advanced simulation tools is now available, which facilitate the modelling and analysis of complex systems. The authors' companies have been utilising the versatility of two such products to simulate complex industrial combined heat and power plant. The potential benefits include improvements in the plant design, control system design and in process operation. This article describes two projects where the specialised power plant simulation tool ACSL/MMS has been used. In the second project, MATLAB/SIMULINK was used to analyse and undertake control design studies on power plant originally simulated using ACSL/MMS.

Two examples of the application of modern simulation tools to combined heat and power plant are presented. The first example documents the dynamic simulation of the Shotton combined heat and power (CHP) plant using ACSL/MMS.[1,2] The complete CHP plant and process plant model was constructed from numerous individual component models. These models were linked and data input via the MMS graphical user interface. The component models were constructed using theoretical relationships based on the conservation of mass, energy and momentum to capture the significant physical effects. Although MMS is supplied with a library of standard power station models, the majority of models used in this example were written at the ALSTOM POWER Technology Centre.

In the second example, ACSL/MMS, ACSL Math[3] and MATLAB/SIMULINK[4,5] were used to investigate strategies for automatic tuning of multiple PI(D) control loops for CHP plant. A tuning procedure was developed based on the identification of linear open-loop process models and the subsequent optimal tuning of the controllers on these models. This procedure has been implemented in MATLAB/SIMULINK and is driven by a custom built GUI (graphical user interface), which enables easy modification of tuning parameters and generates updated closed-loop response plots as the tuning progresses. The developed auto-tuning algorithms were validated by application to a detailed model of a heat recovery steam generator (HRSG), constructed in ACSL/MMS. The interface between the two simulation environments was realised by using ACSL Math.

Shotton CHP plant dynamic modelling

Plant description

A CHP plant with a gross electrical output of approximately 220MW (assuming no process steam production) is currently being constructed in Shotton, North Wales. This plant will supply electricity to an adjacent paper mill and/or the national grid, and process steam to two paper machines in the paper mill. The paper mill is owned by Shotton Paper Company plc, a member of the UPM_Kymmene Group. The CHP plant is shown in Fig. 1 and consists of two gas turbines, two dual pressure heat recovery steam generators (HRSG) and one steam turbine. The steam turbine will accept steam from both HRSGs and will use an air cooled condenser to condense the exhaust steam. Low-pressure steam will be bled from the high-pressure steam turbine exit and piped to an indirect contact heat exchanger to raise process steam for the paper mill. The steam extracted from the steam turbine is condensed during the heat-exchange process and returned to the CHP plant deaerator as condensate. The two steam systems are segregated due to the different water quality requirements of the generation

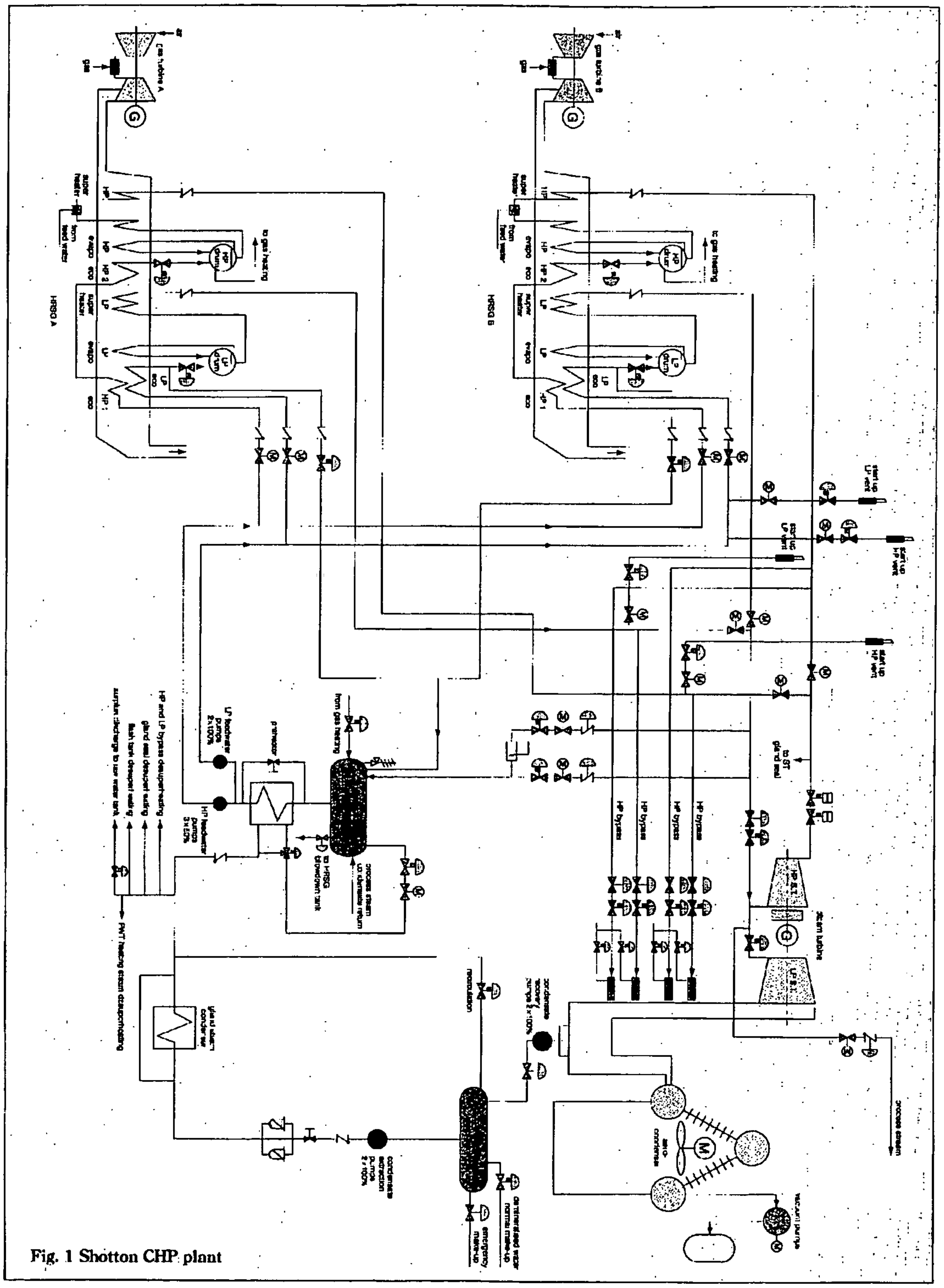


Fig. 1 Shotton CHP plant

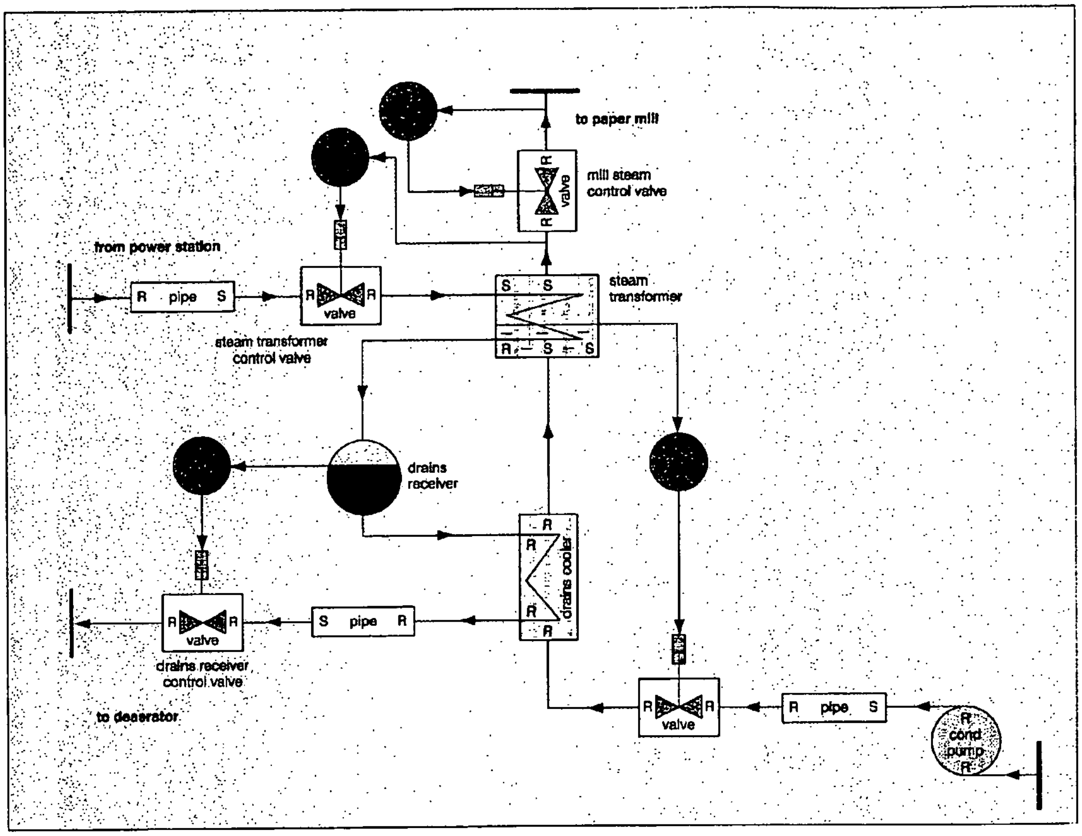


Fig. 2 Shotton process plant layout

and mill steam systems. A diagram of the process plant is shown in Fig. 2.

Often CHP plant is more complicated to control than conventional power plant because of the requirement to satisfy both electrical power and process steam demands. This is particularly true when the condition of the process steam has to be accurately controlled. The requirements of a CHP plant are usually unique and a control strategy has to be designed for the particular plant. To speed up design and reduce delays during commissioning, dynamic models are increasingly being used to test the proposed control system and component interaction.

Shotton dynamic model

To construct the dynamic model, a steady-state model was first used to calculate the values of key process variables with the power station operating at 100% electrical load. Physical data (dimensions, metal masses etc.) for each component was then acquired from the supplier. The whole plant dynamic model was developed and tested in modules—deaerator, HRSG, steam turbine, condenser and process steam plant. Each module was first set up with limited control to run at the 100% steady-state case. Once the model performance at this condition was satisfactory, the full plant controllers were added to enable the model to operate at other loads. The MMS model of the deaerator module is shown in Fig. 3, where each icon represents an ACSL component model. Clicking on an icon produces a list of parameters that can be set by the user. Once the module has been graphically created and parameterised, it is compiled and linked to steam tables and other library routines to form an executable model.

To verify each module within the dynamic model, it was run to 80% and 60% load and the performance at the steady-state condition compared with the performance predicted by the steady-state model. To further verify the model, supplier data for the part load performance was also obtained where possible.

To ensure that joining the modules together to complete the power station model was straightforward, great care was taken to set up each module to the same steady-state condition. Consequently, linking the modules and running the resulting whole plant model to the 100% operating condition caused few problems. The completed model contained approximately 330

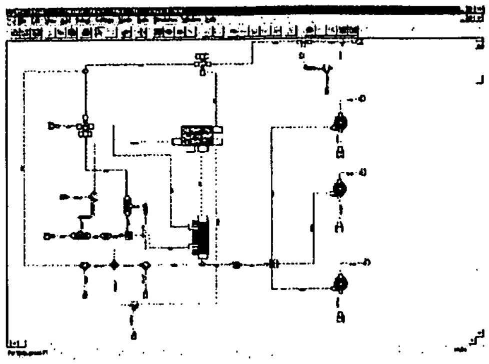


Fig. 3 Deaerator module layout

component modules and 240 state variables. The wide variation in the model time constants necessitated the use of a stiff solver algorithm.

During the development of the whole plant model, several of the component models had to be amended to accurately reflect the design at Shotton. Additionally, new air-cooled condenser and steam heat exchanger modules had to be written.

Using the dynamic model

The main purpose of the CHP plant is to provide electricity and steam to the Shotton paper mill. In the event of a paper break on one of the two paper machines, the process steam requirement will reduce by approximately 50%. The power plant control systems have to accommodate these changes in process steam requirement and be able to rapidly supply process steam when the paper sheet is re-established.

Following discussions with the paper mill operation and process personnel, a set of test scenarios was used to determine the accuracy of the model. Some of these scenarios are detailed below.

To investigate plant performance during start up of the paper mill, the model was set up to open the process steam supply valve to the paper mill at the rate of 10% per minute. The resulting paper mill process steam mass flow rate and the generated electrical power transients are shown in Fig. 4

The effect of the load change on the levels in the high and low-pressure steam drums of HRSG A is shown in Fig. 5. This Figure shows that the load change has very little effect on the HP steam drum level, but does cause a disturbance in the LP steam drum, which is controlled. This disturbance is due to the change of pressure in the deaerator, which is a result of the condensed process steam being fed directly into the deaerator (see Fig. 2). The LP system of the HRSG supplies steam to the deaerator and is consequently influenced by deaerator pressure fluctuations.

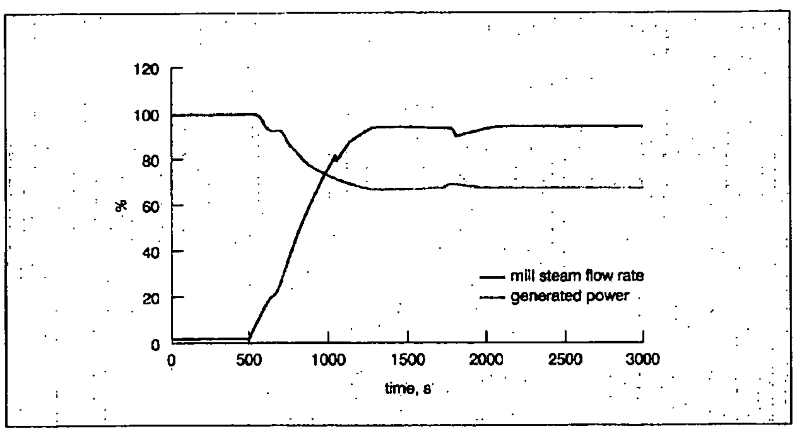
Having demonstrated that the plant can run up to full load at the relatively slow rate of 10% per minute, the plant response during a break in a paper sheet and the resulting very rapid decrease in the process steam flow rate to the paper mill was simulated by reducing the set point of the process steam valve by 40% in 10s. Fig. 6 shows the reduction in process steam flow and the corresponding rise in generated electrical power. The action of the steam heat exchanger control valves is shown in Fig. 7.

It was found that, if the drains receiver level control valve operates too slowly, it can significantly reduce the tube side pressure in the steam transformer. This leads to the tubes starting to fill with saturated vapour, which in turn affects the heat transfer characteristics of the steam transformer. Using the model, it is possible to arrive at valve response times that are acceptable.

Fig. 8 shows the changes in condenser and steam drum levels during the reduction in process steam flow rate. The condenser level rises because of the increase in flow rate through the LP steam turbine. The deaerator level initially decreases due to the reduction in condensate being returned from the steam heat exchanger directly to the deaerator.

A final test of the control system was to reduce the load

Fig. 4 Paper mill full load acceptance



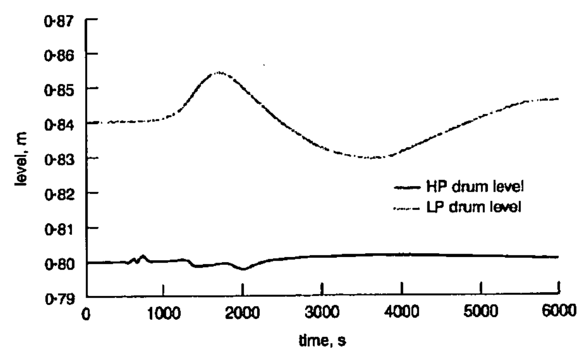


Fig. 5 Steam drum levels during load acceptance

of each of the gas turbines from 100% to 70% (at 10% per minute), with the paper mill operating at part load. In practice it should be possible to carry out this procedure with a minimum of disruption to the paper mill process steam flow.

The generated electrical power and process steam mass flow rate are shown in Fig. 9. The Figure shows that the process steam flow rate remains constant whilst the generated electrical power reduces, as required.

Fig. 10 shows that, to maintain the process steam mass flow rate, the LP turbine governor valve has closed, thereby maintaining the HP steam turbine outlet pressure. The HP turbine governor valve has only moved slightly.

Discussion

This section has briefly described a modelling exercise undertaken on a real CHP plant whilst in the design stage. Considerable effort has been invested in developing an accurate, theoretically based model, but the potential savings in time and money that can be gained by identifying design and control issues early make this a worthwhile exercise. Time spent addressing such issues during the commissioning phase of the plant can be extremely costly. Not only does the dynamic model give control engineers a very good understanding of how the many plant components will interact during steady-state and transient operation, but also it provides a facility to test and verify control strategies. At the time of writing, testing of the model is not yet complete, and several areas worthy of further investigation have already been identified.

The next stage in the model development will be to add the validated model of the process steam distribution system and its control logic. Using this model, plant behaviour during specific events in the paper mill can also be simulated.

Using the modular approach of ACSL/MMS, power station models can be rapidly assembled via the MMS graphical interface. Additionally, the mathematical solvers supplied with ACSL are particularly good at giving numerically stable solutions relatively quickly.

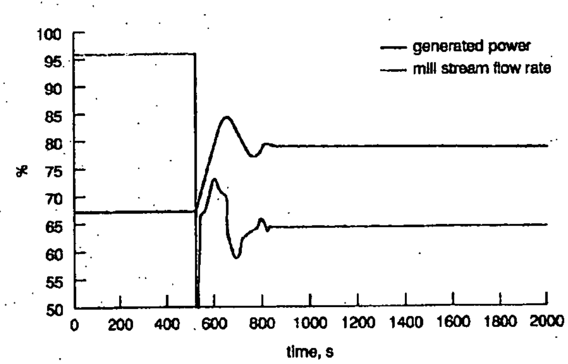


Fig. 6 Plant behaviour during paper break

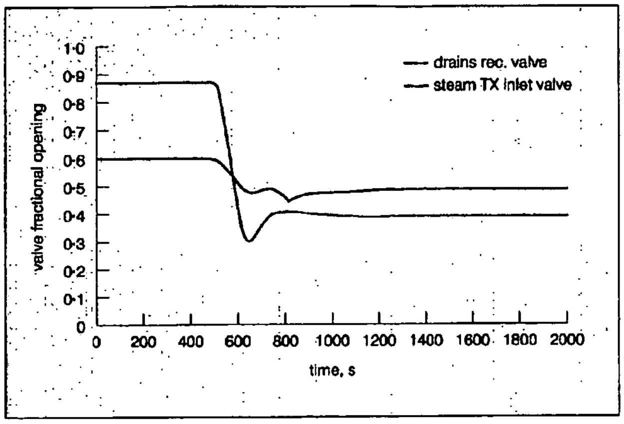


Fig. 7 Steam TX control valve action

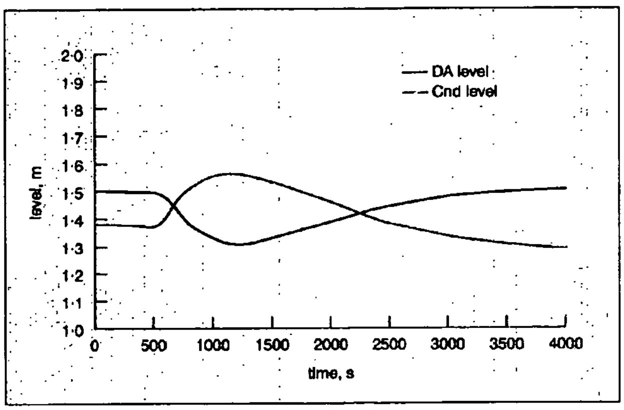


Fig. 8 Deaerator and condenser levels

Control loop tuning

Project background

The typical control technology implemented in modern power plants is DCS based, with multiple PI(D) loops including feed-forward and cascade control architectures. A significant problem for the commissioning engineers is to determine appropriate settings for the individual control loop gains, so that the plant is controlled in a safe and efficient manner across the whole of the operating envelope. Currently the most common practice is based on previous operations experience and on a 'try it and see' ad-hoc strategy. ALSTOM Power is engaged in the control design for a variety of power plant including CHP plant. For the purpose of properly assessing the overall control performance a detailed plant dynamic model is developed in ACSL/MMS.

The HRSG is a major subsystem of the overall CHP plant model and has been used in a simulation casestudy to develop automatic PI(D) control loop tuning algorithms. The primary PI(D) control loops for the HRSG—ordered from fastest to slowest—are as follows:

- steam drum feedwater controller
- HP turbine inlet pressure control
- steam drum level controller
- deaerator level control
- deaerator pressure control
- deaerator temperature control.

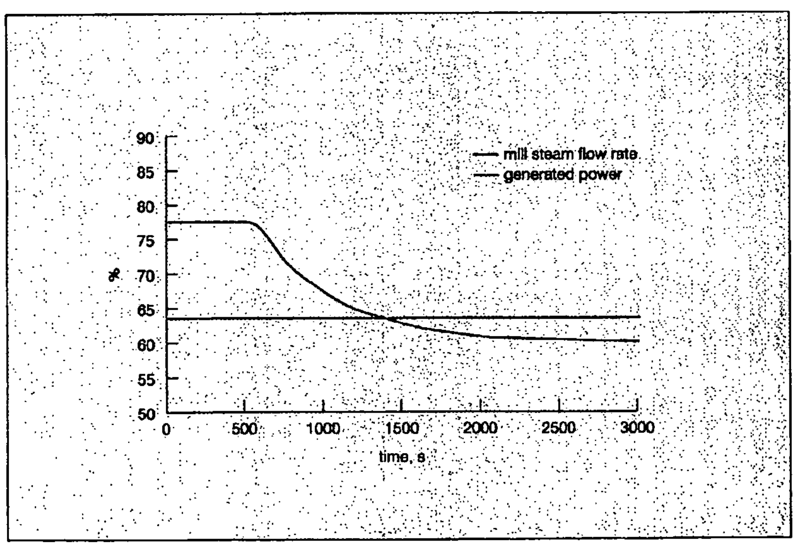


Fig. 9 Plant behaviour during GT load reduction

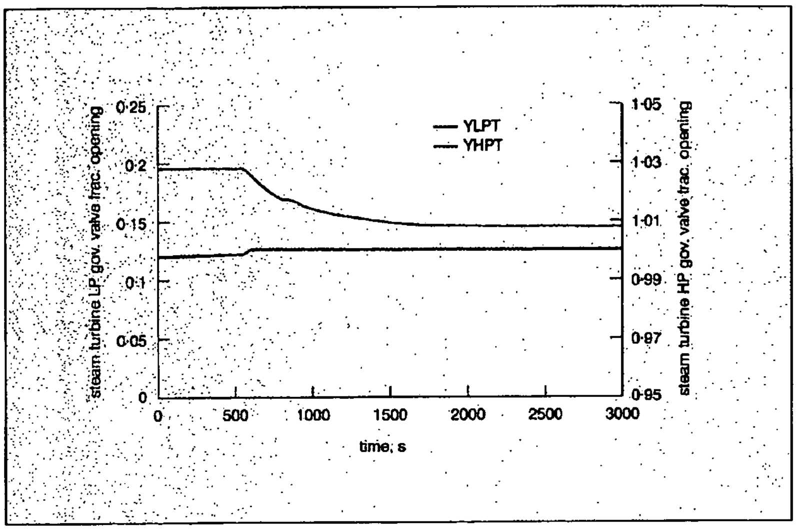


Fig. 10 Steam turbine governor valves

Note that all the above loops are operated with fixed set points across the whole of the normal operating envelope of the CHP plant.

Sequential loop tuning of the HRSG

The method of tuning single loops sequentially, in the order fastest first through to slowest last, has been demonstrated to yield acceptable results in power plant applications,[6] and has been applied in an HRSG simulation case-study. The procedure adopted for tuning a single loop was as follows:

- Step 1: perform a system identification experiment
- Step 2: derive a dynamic model of the process to be controlled from the experiment data
- Step 3: implement the model in a closed-loop simulation, where an optimisation algorithm adjusts the controller PI(D) gains to improve the observed disturbance rejection performance from iteration to iteration
- Step 4: if the closed-loop simulation responses are considered to be satisfactory, then the tuned PI gains may be transferred to the real controller.

Step 1 was carried out using ACSL/MMS in conjunction with ACSL Math.[3] ACSL Math is an add-on tool to ACSL. It is quite similar to MATLAB; however, the integration of ACSL Math with ACSL only goes as far as running ACSL models and post-processing the simulation results. There is no equivalent to the m-code S-function of MATLAB/SIMULINK and the library of available functions is limited in comparison to MATLAB.

The applied identification test signal consisted of a small number of successive steps, as shown in Fig. 11. Note that the use of pseudo random binary (PRBS) test sequences, although ideal from a process information generation point of view, may often not be acceptable to the commissioning engineers.

The data collected from the system identification experiment was then loaded into MATLAB and the system identification toolbox[7] was utilised to achieve

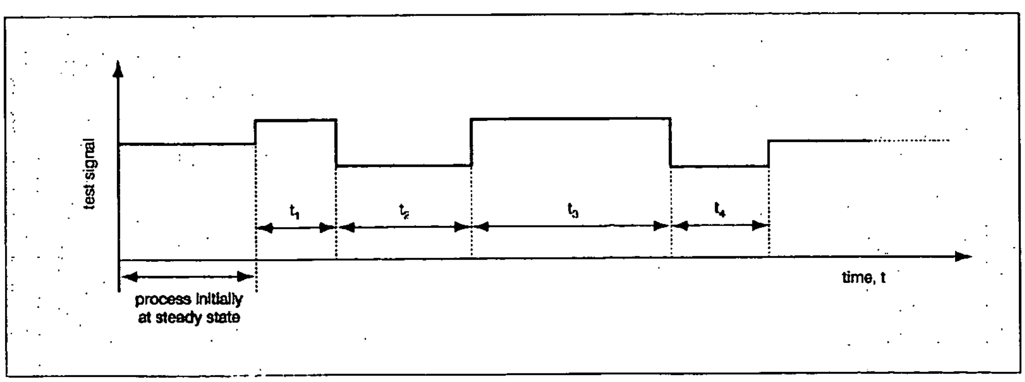


Fig. 11 Successive steps test signal

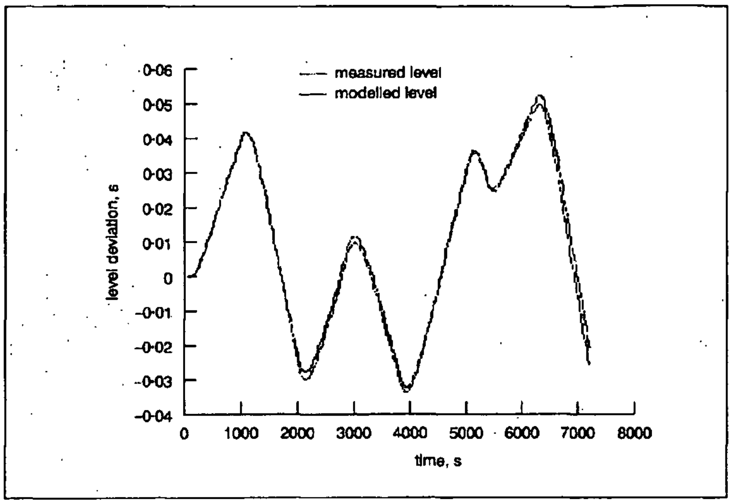


Fig. 12 ACSL/MMS nonlinear model (the measured level) and the identified linear model steam drum level deviation in response to set point changes

step 2. An identified linear model of the drum level variation is shown in Fig. 12. Note that, in the case of integrating (or unstable) processes such as the drum level, it is not normally possible to disconnect the controller, and therefore the system identification experiment must be conducted in closed loop, with the test signal applied to the controller set-point.

Once a satisfactory model of the process dynamics has been obtained, it is then transferred to a standardised SIMULINK block diagram (Fig. 13). This is used to obtain predicted closed-loop responses for candidate controller gain settings, during the control loop tuning (*step 3*).

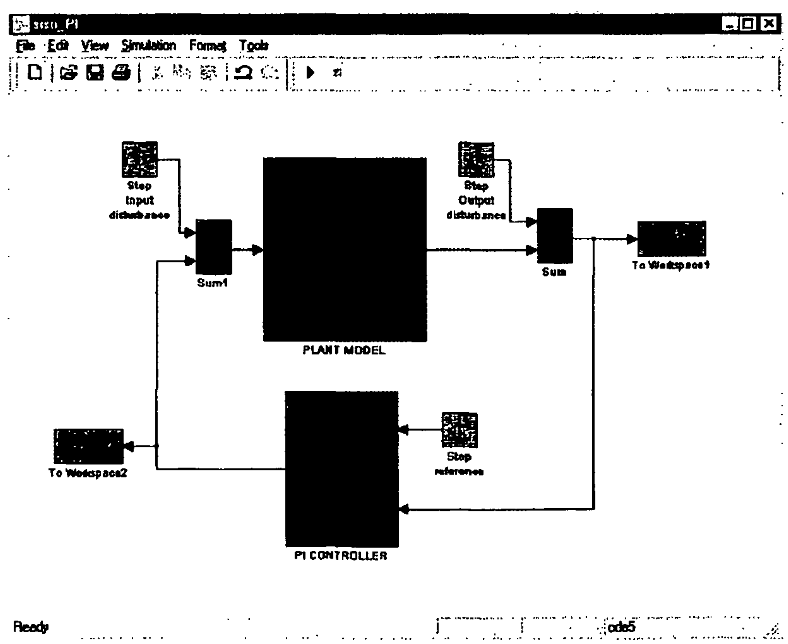
The tuning objectives were specified as a feasible region in the error-time and control output-time plane, as shown by the dotted regions in Fig. 15. The boundaries of the error-time region are set according to user-defined specifications for peak overshoot, settling time and steady-state error.[8,9] To provide ready access to all the tuning program functions, a custom GUI was developed (Fig. 14).

During tuning, the improvement in the closed-loop responses from iteration to iteration is displayed via continuously updated plots. For the drum level loop the pre-tuning and tuned closed-loop responses to a 10% step output disturbance are as shown in Fig. 15. On transferring the tuned gains to the MMS drum level controller (*step 4*), similar responses to that observed for the identified model are obtained.

HRSG global disturbance rejection test

After tuning all the primary HRSG control loops, a global disturbance rejection test was performed using the

Fig. 13 Standardised closed loop tuning SIMULINK block diagram



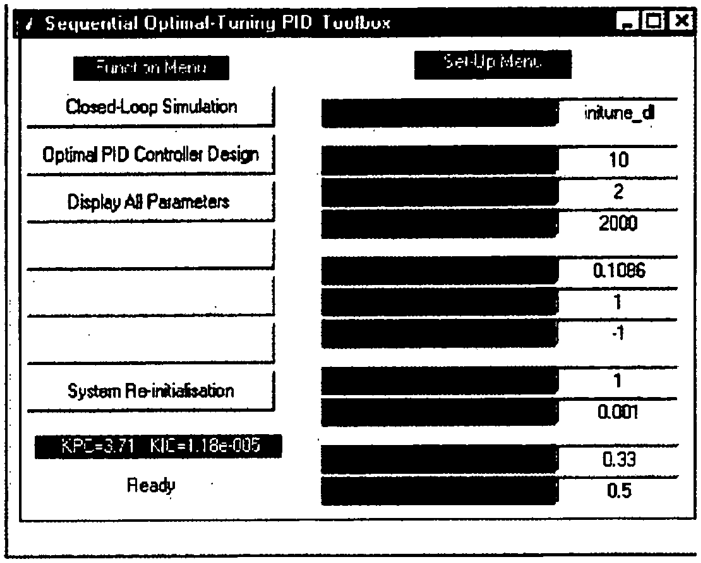


Fig. 14 GUI for control loop tuning

ACSL/MMS nonlinear HRSG model. The response to a 50% step reduction in the gas turbine exhaust gas flow was simulated. It can be seen from Fig. 16 that a significant improvement in overall disturbance rejection performance has been achieved by the application of sequential loop tuning.

Potential for real application

It is anticipated that the developed tuning tools will be applied during the commissioning of a CHP plant currently under manufacture. Of course, real applications do not enjoy the idealised environment of a simulation study, and issues such as unmeasured process disturbances and measurement noise contribute to making the model identification and control-loop tuning tasks considerably more difficult. Initially, therefore, the method will be used as a guide to aid commissioning engineers whilst operational experience is gained.

Conclusion

In this article, two industrially motivated simulation studies have been presented:

- dynamic modelling of the Shotton CHP plant
- multiple control-loop tuning which possesses general relevance to all power plant designs.

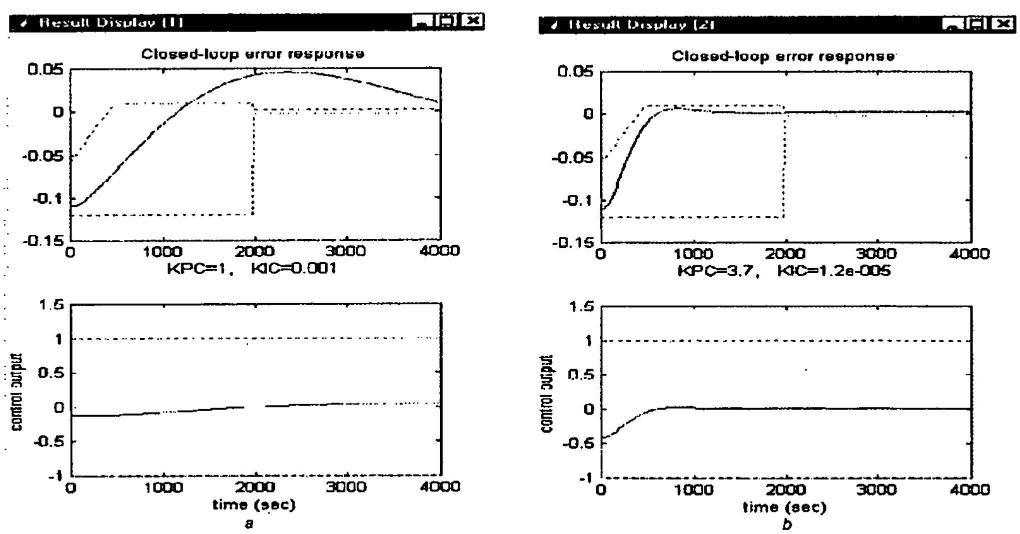


Fig. 15 Drum level loop tuning : (*a*) Pre-tuning; (*b*) Post-tuning

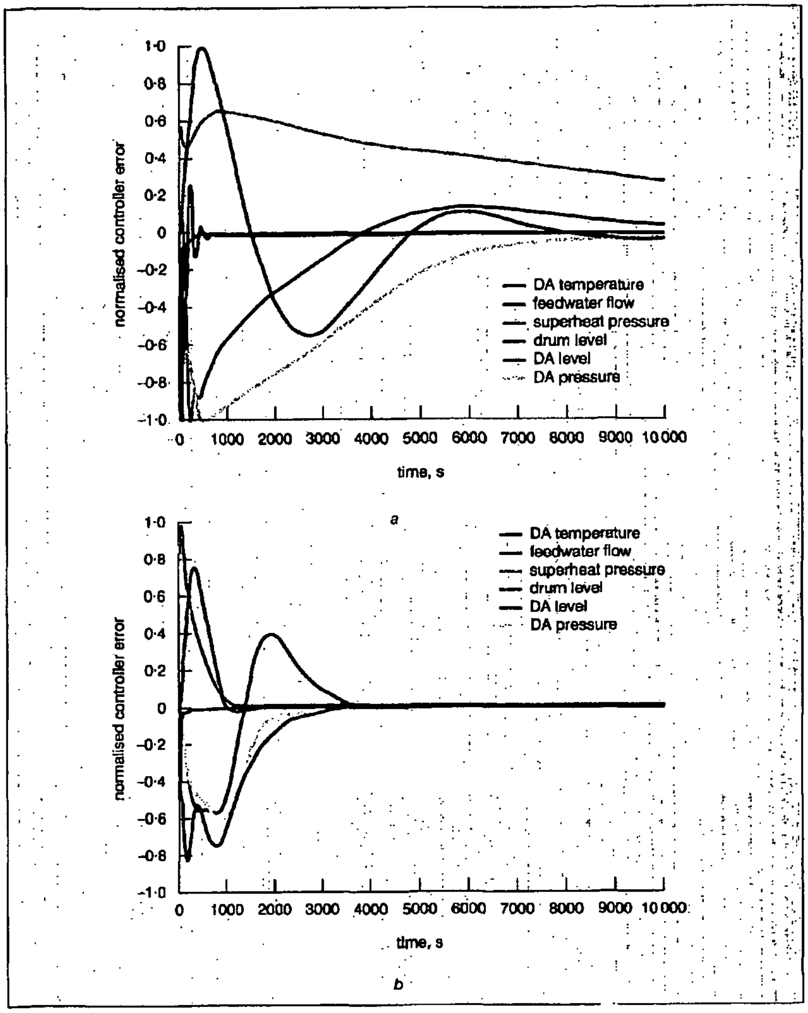


Fig. 16 HRSG response to 50% step reduction in GT exhaust gas flow, (*a*) pre and (*b*) post control loop tuning. Note: signals are normalised by peak absolute controller error in each case

The considerable versatility of modern simulation tools, in aiding both the plant design and control design tasks at an early stage of an industrial project, has been demonstrated. Time spent addressing such issues during the commissioning phase of the plant can be extremely costly. A rigorous dynamic model enables engineers to gain a very good insight into how the many plant components will interact during both steady-state and transient operation. It also provides a facility to test and verify control strategies.

Acknowledgment

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M. S. Donne and A. W. Pike are with ALSTOM POWER, Technology Centre, Control Group, Whetstone, Leicester, UK. R. Savry is with ALSTOM POWER, Electrical & Control Systems, Knutsford, Cheshire WA16 8GE, UK. E-mail: andrew.pike@power.alstom.com